Angle-of-arrival-assisted Relative Interferometric Localization Using Software Defined Radios

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***Abstract*—In this work, we present SDR-ARI – a Software Defined Radio (SDR) approach to an Angle-of-arrival-assisted Relative Interferometric (ARI) RADAR transceiver. It has a number of desirable attributes including the ability to reduce the synchronization, network, and hardware requirements when operating as the sole RADAR modality and its ability to augment existing pulsed and CW RADAR algorithms. While, ARI encoding was initially proposed in prior work, no implementation had been completed and only a pure hardware approach to the receiver was reported. We have developed and implemented a software-defined model in Matlab, and have designed, simulated, and implemented an SDR-ARI transceiver utilizing USRP hardware and gnuRadio software. The use of software-defined radio has allowed us to implement ARI in a timely manner. The proposed approach is described and analyzed.**

I. Introduction

An Angle-of-arrival-assisted Radio Interferometry (ARI) based system consists of transmitting beacons and passive receive-only objects each of which is equipped with a steerable directional antenna. Each of the beacons knows its location and orientation. Each beacon transmits a unique pair of frequencies creating a beat envelope in the transmitted signal which is not unique to any beacon. The receiver can then identify scattering targets in the intermediate environment through the intersection of the beacon boresights (Angle of Arrival – AoA) fused with the Phase Difference of Arrival (PDoA) information, which is the phase comparison of the signals recovered from each beacon's beat envelope [1].

The ARI approach offers a number of unique advantages. Since, all of the required transmitter timing information is encoded in the signal, an object's receiver does not need to maintain phase coherence with the time source of any beacon. Further, the beacons are almost immune to phase coherence errors in their carrier needing only to maintain sync amongst beacons at the modest frequency of their beat envelope. The directive nature of ARI and its ability to preserve transmitter identity assists in disambiguating phase-based distance relationships which are, otherwise, only disambiguous for the region $\langle -\pi/2, \pi/2 \rangle$ and, adding orientation knowledge, allows 3D localization from a mathematical minimum of just two beacons and one object [1]. As the objects are passive, an ARI based navigation system would scale, fitting an infinite number of objects in finite bandwidth while protecting their presence and identity from observation. An ARI system allows the electromagnetic (EM) frequency of operation and the abstract wavelength of localization to be determined independently since the location information rides on a carrier which is the *difference* in two physical carrier frequencies. As such the transmitters may be placed very close together (if desired) – even at tiny fractions of the localization wavelength. This configuration is especially advantageous when using ARI in a pulsed configuration [4].

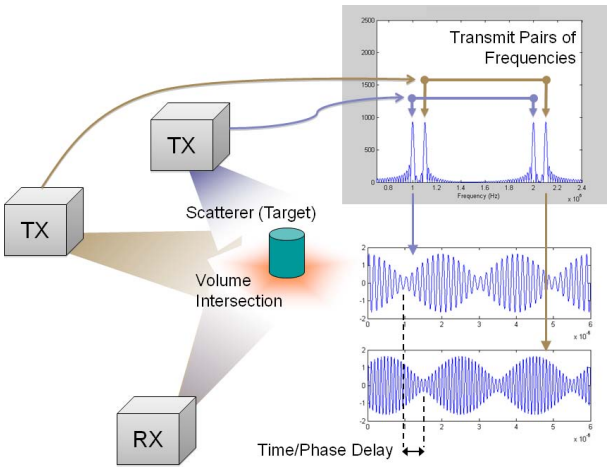


Fig. 1. A Software Defined Angle-of-arrival-assisted Relative Interferometry (SDR-ARI) based system consists of transmitting beacons and passive receive-only objects each of which is equipped with a steerable directional antenna. The beacons transmit unique pairs of frequencies creating a beat envelope which is not unique to any beacon.

ARI encoding was initially proposed in [1] using Continuous-Wave (CW) transmission and a principally analog receiver. Subsequent work [4] demonstrated the possibilties for Pulse-Wave (PW) operation. In this work, we endeavour to reduce the development time and implementation cost for ARI-type systems. To that end we have designed, simulated, and implemented a Software Defined Radio (SDR) Angle-of-arrival-assisted Relative Interferometry (ARI) transceiver for position estimation recovery through the use of USRP [2] hardware and gnuRadio [3] software. The proposed approach is described and analyzed.

II. Software Defined Radio Approach to ARI

The use of Software Defined Radio [5] in our implementation of the ARI system has added several very important advantages. Unlike analog processing, Digital Signal Process-

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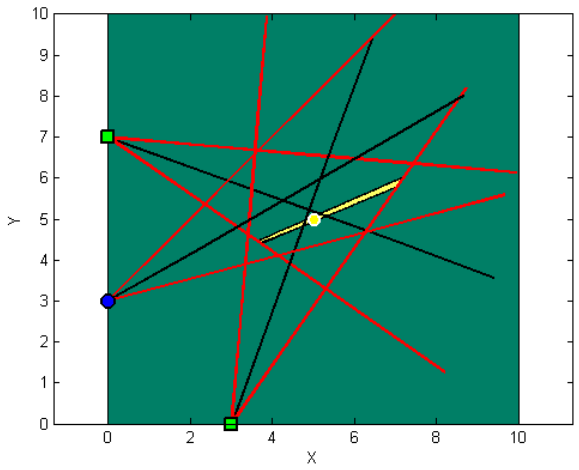


Fig. 2. The phase difference of arrival estimates the target position to within a smaller volume and a substantially smaller angle faster than traditional AoA RADAR approaches. The squares are transmitters, the dark circle is the receiver, and the central circle is a non-cooperating target [1].

ing (DSP) does not accumlate appreciable noise and may be re-tuned or reprogrammed dynamically. These attributes could be exploited in an SDR-ARI system to perform Doppler tracking, dynamically select the frequency band, and perform adaptive power thresholding. A Software Defined approach also allows for a lower implementation cost due to fewer precision components.

Under ARI encoding a unique property emerges that is well-exploited by an SDR approach, namely, that the frequency chosen for electro-magnetic propagation (carrier) may be selected independently of the frequency chosen for localization. The carrier frequency may be moved at will and the localization components continue to function unaffected. This flexibility may be exploited to continue service provision in the event of hostile jamming, interference, or the detection of the primary user's denial pilot tone.

II.A. Nomenclature

For clarity, and to maintain consistency with prior work, we will use f_{x_n} to refer to individual frequencies, where x is a generic transmitting beacon, a specific transmitting beacon ($x = a, b, c...$), or a receiving object ($x = r$). n is the frequency designator ($1, 2,$ or c for carrier) for the ARI component indicated by x. We do not designate objects individually since the objects (receivers) are passive and may be considered independently.

II.B. Transmitter

All of the transmission components have direct analogies in the digital synthesis domain. Consequently, there is little architectural difference between a hardware or software approach.

II.C. Receiver

Unfortunately, implementing an SDR-ARI receiver architecture is much more complex than implementing the transmitter.

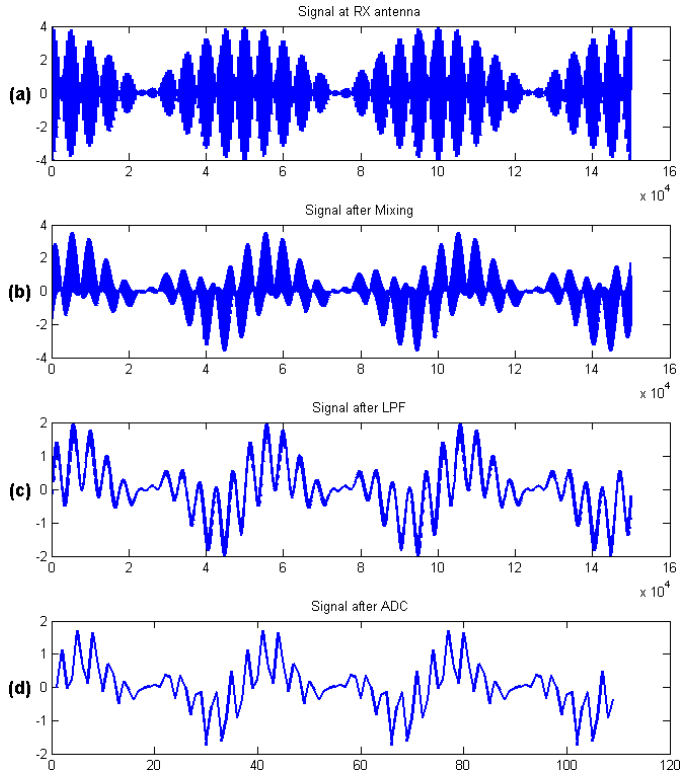


Fig. 3. Signal reception from analog to digital. (a) The recieved signal at the antenna; (b) The signal after mixing; (c) The signal after low-pass filter; (d) The signal after sampling.

Given the limitations of software radios in general, SDR's use a hardware downconversion Analog Front End (AFE) to bring the signal within the sampling system's bandwidth. In this respect, it is indifferent from a pure hardware approach. In either case, our receiver consists of detection, down-conversion (mixing then filtering), and processing. For illustration, these processes are shown in figure 3, in the time domain, using our Matlab model.

The sampled signal prior to any further processing consists of equation 1:

$$S_{rx} = S_{f_{a_1}} + S_{f_{b_1}} + S_{f_{a_2}} + S_{f_{b_2}} \tag{1}$$

...where S_f refers to a sinusoidal signal at frequency f.

II.C.1. Analog Hardware Architecture: A complete hard radio approach in analog hardware is shown in figure 4(top). The Beacon Specific Blocks (BSB) each contains the appropriate channel selecting filters and a pair of Variable Gain Amplifiers (VGA) that are used to equalize the amplitudes of the two frequency components (f_{x_1}, f_{x_2}). This maximizes the amplitude of the recovered f_{com}. The equalized output from each beacon at f_{com} is compared in a phase detection unit for which numerous analog approaches are known.

II.C.2. SDR via Time Domain Filters: After down-conversion in hardware, the signal is now within the sampling bandwidth of the software radio. The USRP uses dual 12-bit 64 Megasample per Second ADCs for capture. In the

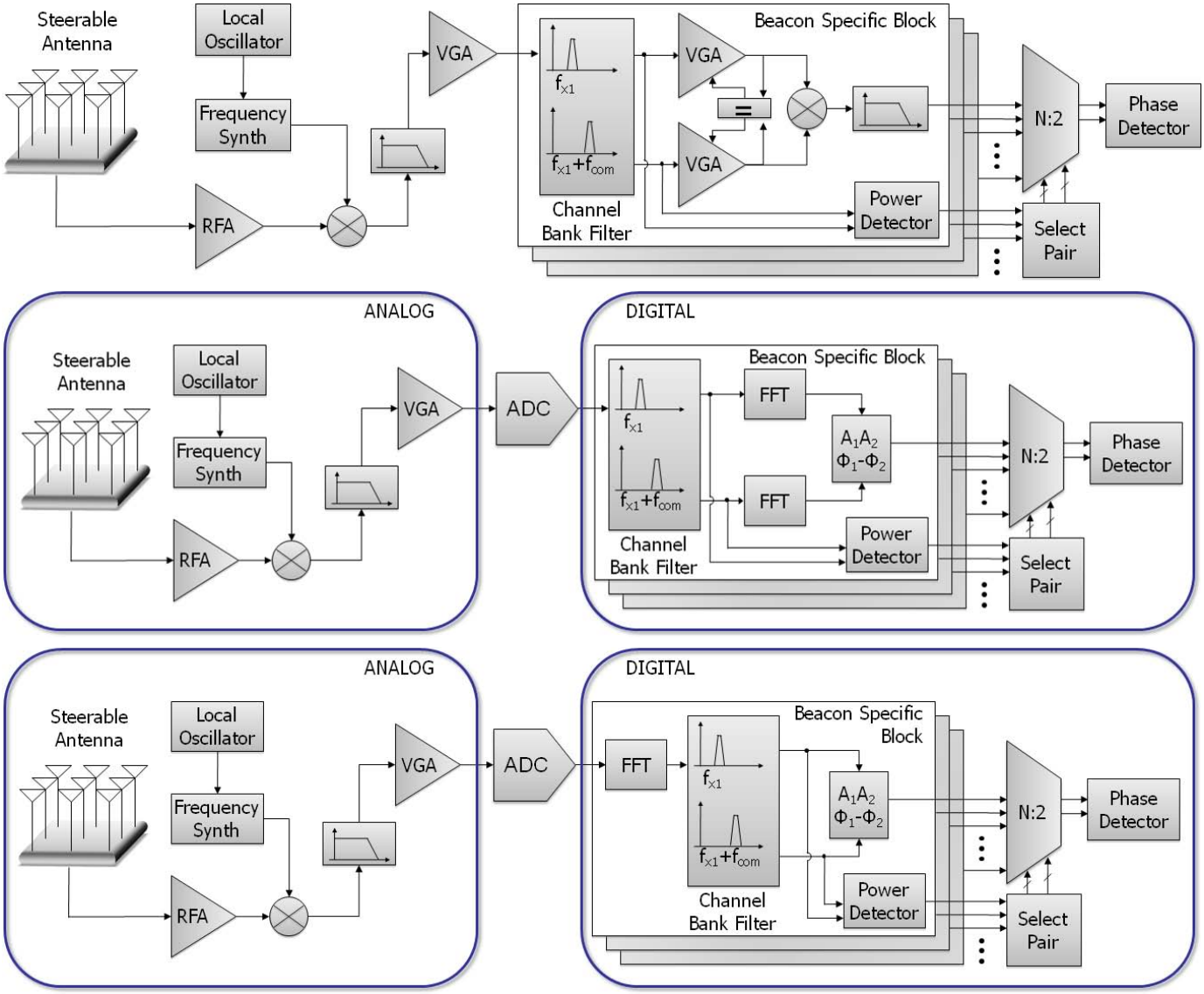


Fig. 4. *(top)* The proposed full-analog superheterodyne down-converter and signal-processing blocks for the ARI receiver [1]. *(middle)* An SDR approach utilizing time-domain filters. *(bottom)* An improved SDR approach utilizing frequency-domain filters.

time-domain a bank of band-pass filters are required to separate $S_{f_{a_1}}$, $S_{f_{b_1}}$, $S_{f_{a_2}}$, etc. from each other as shown in figure 5. However, the most memory and processor efficient high-quality (Q) filter architectures (such as Butterworth and Chebyshev [6]) sacrifice linear phase response, which compromises localization performance. Alternatively, linear phase response may be achieved at sufficient Q with lengthy filter chains increasing hardware cost, delay, and scan time. Given that each component frequency must be isolated, the number of filters required is equal to the number of beacons in a simultaneous search operation multiplied by two.

Once the signal frequencies are isolated, an equivalent approach to the hardware of figure 4(top) is possible. The complete architecture utilizing these time-domain filters is shown in figure 4(middle). In which the equalizing, mixing, and phase detection are indicated by an FFT followed by a block representing the math of equations (2) through (5). The authors recognize that time-domain approaches exist and that this is not an optimal path, but it will prove illustrative as a comparison to the frequency-domain approach which now follows.

II.C.3. SDR via Frequency Domain Filters: The architecture of figure 4(bottom) is substantially more resource and run-time efficient. Whereas the band-pass filter bank in the time-domain required long signal chains for each component frequency, frequency isolation in the frequency-domain is trivial – we simply select the freqeuncy bin, from within a band of freqeuncy bins around our target frequency f_n, with the largest magnitude. This process is illustrated in figure 6 for the four individual signals at f_{a_1}, f_{b_1}, f_{a_2}, and f_{b_2}.

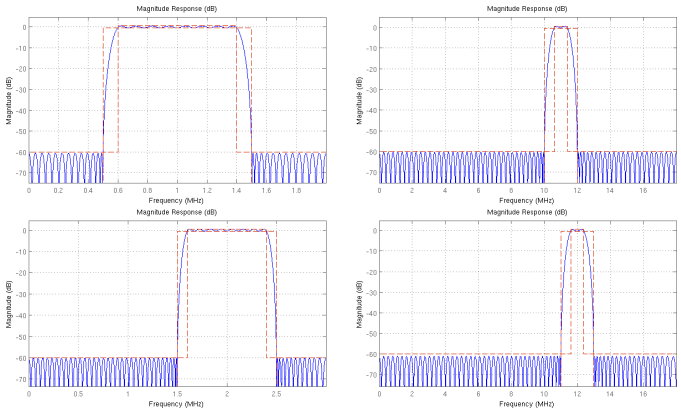


Fig. 5. The Band-Pass Filter bank in the Time Domain.

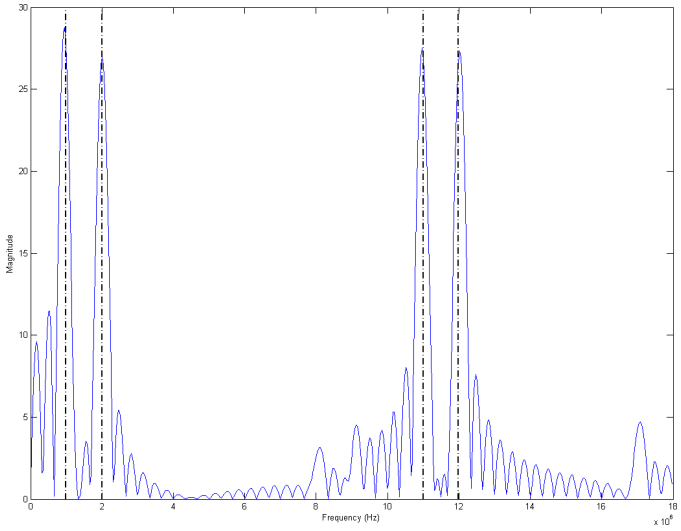


Fig. 6. The Band-Pass Filter bank in the frequency domain.

II.D. Phase Recovery

Once we have isolated the signals at the four desired frequencies, we are able to extract the amplitude and phase information from each signal. This process is described mathematically by:

$$\sin(2\pi f_2 + \phi_2) \times \sin(2\pi f_1 + \phi_1) \tag{2}$$

$$\frac{1}{2}\cos(2\pi f_2 + \phi_2 - 2\pi f_1 - \phi_1) + \tag{3}$$

$$-\frac{1}{2}\cos(2\pi f_2 + \phi_2 + 2\pi f_1 + \phi_1)$$

$$LPF \Rightarrow \frac{1}{2}\cos\left(2\pi\left(f_2 - f_1\right) + \phi_2 - \phi_1\right) \tag{4}$$

$$\phi_{f_{com}} = \phi_2 - \phi_1 \tag{5}$$

where LPF is a Low Pass Filter function which removes the high frequency term at $f_1 + f_2$, the last term of equation (3).

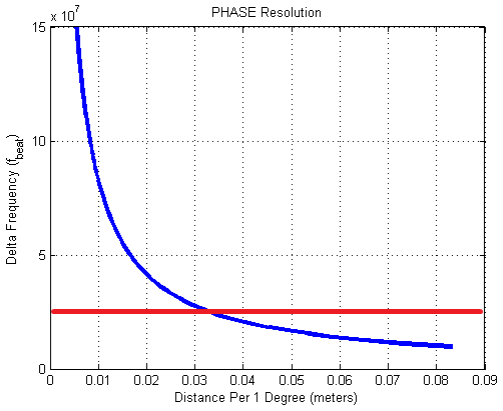


Fig. 7. Linear resolution as a function of $f_{com}/2\pi$, or 1 degree of phase. Values below the horizontal limit line *(red)* are achievable with current low-cost SDR systems.

III. SDR Feasibility

Determining the optimal value of f_{com} is not trivial. Resolution suffers as shown in figure 7. A large value of f_{com} requires a wide spectrum gap between each beacon's component frequencies. This, in turn, has significant implications for the hardware design, which is generally more difficult to implement as sampling rates go up and phase margins tighten. Increasing the common frequency also necessitates increasing the sampling rate to stay above the Nyquist limit. $f_{com} > 24MHz$ is presently unattainable in low-cost SDR platforms [2]. This limit line is plotted in the figure.

In order to use the available spectrum most efficiently and to optimize the hardware implementation, ARI employs a frequency interleaving scheme (see figure 1). This allows the limited bandwidth of our SDR platform to achieve maximal values of f_{com}. The f_{x_1} frequencies are all clustered into one band and their corresponding f_{x_2} frequencies into another. The use of this dual band approach is expedient, allowing a maximum f_{com} in any finite bandwidth.

The performance of an SDR system under ideal conditions, in contrast to a hardware system under equally ideal conditions, will uniquely suffer from quantization noise introduced by its digital nature. Figure 8 shows the phase transfer function of the entire system end-to-end.

After a linear fit is applied the error is releaved to be quite small as indicated in figure 9. This error corresponds to less than 8cm of free-space length.

It is extremely difficult to syncronize the carriers of two independent SDR platforms [7]. Fortunately, ARI encoding is substantially insensitive to phase differences in the carriers between beacons. As such, the envelope shows a near-stationary phase as the component carriers phase shift beneath it. In the time domain, as shown in figure 10, phase shift is not apparent in the data signal despite significant shift in the intermediate signal.

In figure 11, this small error is shown in greater detail. SDR-ARI is only minorly effected, $< \pm 1°$, by incoherency among

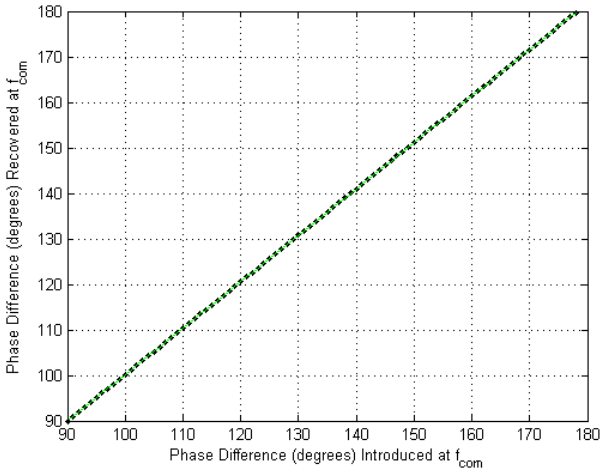


Fig. 8. The end-to-end phase transfer function of the SDR-ARI model including up-conversion, down-conversion, and signal processing. A linear fit is plotted in the figure

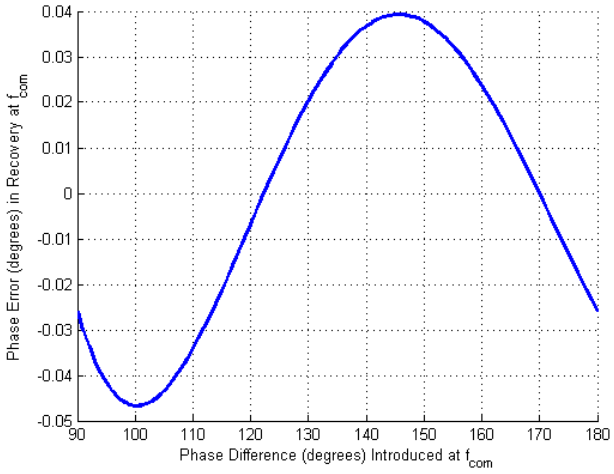


Fig. 9. The end-to-end phase transfer error with respect to a linear fit. The error comes predominantly from quantization noise during signal reconstruction.

the beacon carriers. Consequently, time synchronization need only occur among beacons at their substantially lower data frequencies – a property which makes an SDR approach feasible.

IV. Implementation

The SDR-ARI platform was implemented on a USRP [2] using GNURadio [3]. The USRP is USB-connected to a host computer system, as in figure 12, and used for transmitting and receiving various signals. In combination with GNURadio, we were able to receive the transmitted signal through a direct connection between the two daughterboards. As illustrated in figure 14, our implementation is capable of isolating received signals in the frequency domain. The SDR-ARI block-diagram implementation is shown in figure 13.

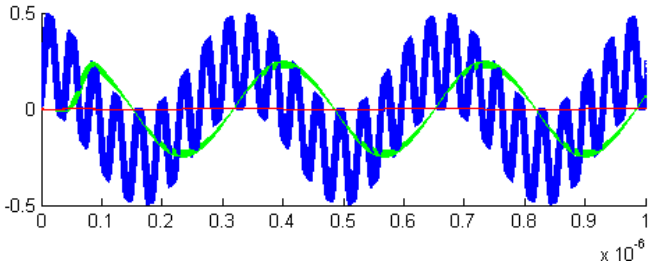


Fig. 10. The principal ARI data signal is relatively unaffected by initial phase error in the carrier signal or in generating a quadrature variant of it. In the time domain, phase shift is not apparent in the data signal despite significant shift in the baseband signal.

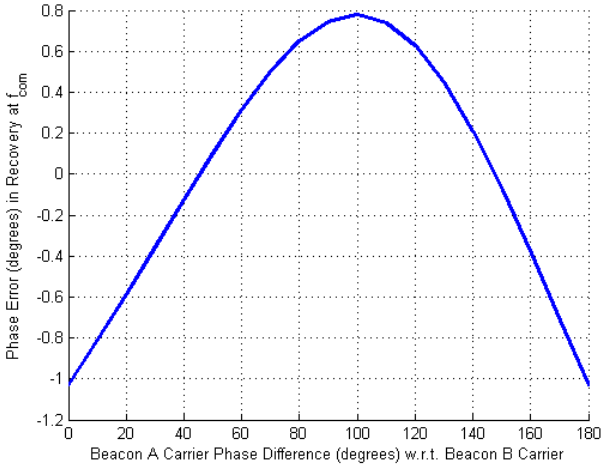


Fig. 11. SDR-ARI is immune to carrier incoherency between transmitters and receivers and only minorly effected, $< \pm 1°$, by incoherency among the beacon carriers. Consequently, time synchronization need only occur among beacons at their substantially lower data frequencies.

V. Related Work

Other indoor location estimation technologies include the use of active Radio Frequency Identification (RFID) systems, where the RFID tags are self-powered in order to identify and locate them. LANDMARC [11], is a location sensing prototype system that uses RFID technology for locating objects inside buildings. Through the use of reference tags, they are able to increase the location accuracy. However, they also face several issues including behavior variation among tags. In spotON [12], another indoor 3-D location sensing technique is developed for object tagging based on RF Signal Strength. Several base stations are used to measure the signal strength that will be mapped to an approximate distance. A central sever is used to triangulate the exact object location with these measurements using an aggression algorithm.

Following the work in [8], the Vanderbilt team developed inTrack, a cooperative tracking system based on radio interferometry [13]. This system is developed to track a mobile sensor with high accuracy in large areas with moderate multipah tolerance. They use XSM motes by Crossbow, running TinyOS operating system. The receivers measure the frequency and

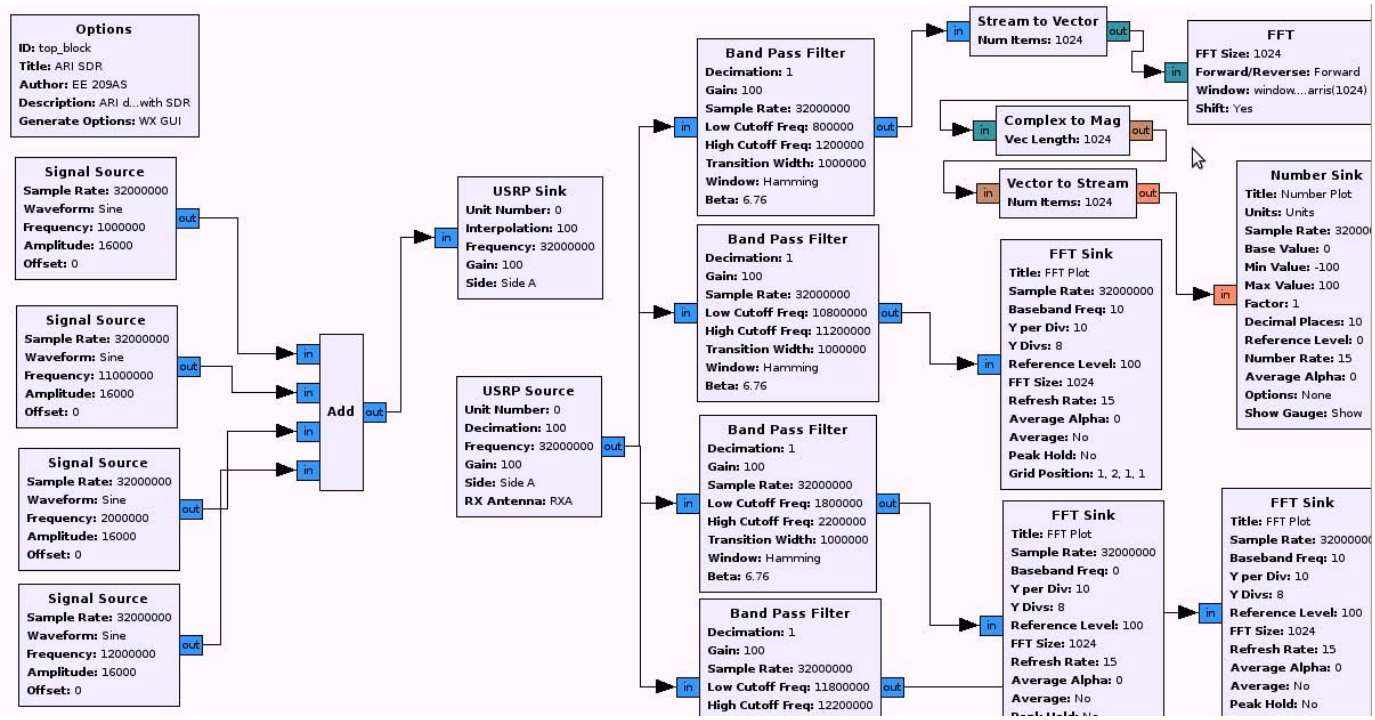


Fig. 13. The gnuRadio data flow diagram for the transmitter (left) and the receiver (right).

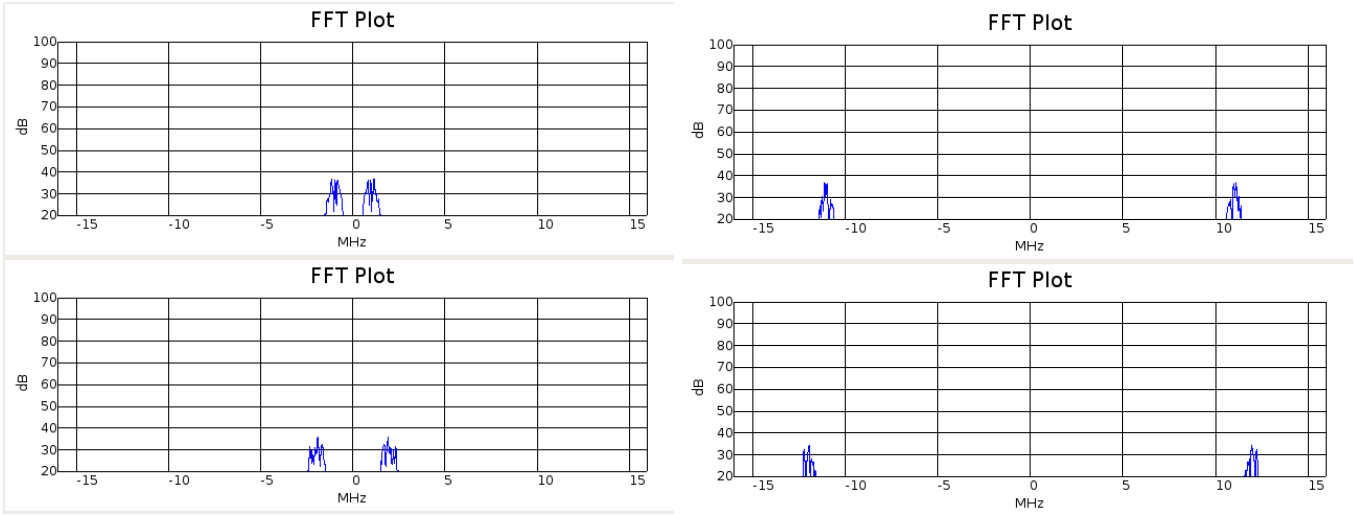


Fig. 14. Operation of our gnuRadio data flow diagram at the ARI unique (left) and common offset (right) frequencies. Here, $f_{com} = 10MHz$.

phase of the interference signal, and using the interferometric ranging algorithm, the server calculates the location of the tracked node. However, in this system, again they require time synchronization between the transmitting nodes, as opposed to ARI-SDR. They are also only able to track a single target.

In [14], another team from Vanderbilt University argues that although radio interferometry has proven successful outdoors [8], it is still not applicable indoors due to its sensitivity to multipath without further theoretical and experimental research. They present their preliminary results, which are implemented on a Software Defined Radio, specifically, gnuRadio [3] and USRP [2] platform. The use of a SDR allows them to use a wide range of frequencies, powerful signal processing capabilities, and gives them flexibility as far as radio protocols. As in [8] the team was facing time synchronization challenges between receivers, they decided not to put this restriction on their design. Instead, they have one of the transmitters embed an indicator in its signal, marking a common point in time for both receivers. Once this is done, the receivers have a common reference from which they can measure the phase of the signal.

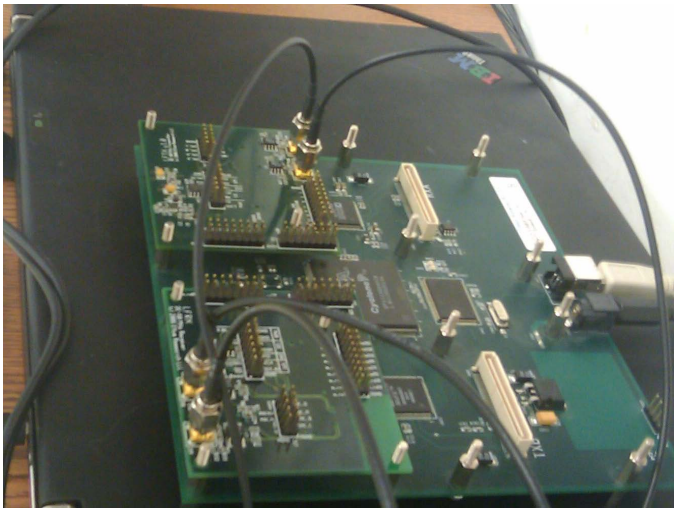


Fig. 12. The Universal Software Radio Peripheral reconfigurable hardware running gnuRadio software during SDR-ARI transmit-recieve testing.

VI. Conclusion

ARI could prove advantageous in a diverse set of military application scenarios. To preserve stealth, reduce power and form-factor, and increase detection range ARI beacons could be placed near vital intersections, along thoroughfares, or deployed and redeployed by recon units. The ARI receiver is then mounted to the lead convoy vehicle which ascertains mine presence from the back-scatter of the beacons. As in GPS, the vehicle mounted equipment is completely passive allowing stealth operation and because the ARI beacons are forward-deployed, detection range and accuracy is improved.

However, to date, no prior viable commodity implementation exists. In this work we have presented the design and implementation of an Angle-of-arrival-assisted Relative Interferometry (ARI) approach to target localization through the use of Software Defined Radio (SDR). We have described the architecural implementation of this system, simulated its operation, instantiated the transceiver signal processing chain in real hardware, and provided an analysis of its performance advantages and disadvantages.

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